Chapter 5. Metallic Biomaterials

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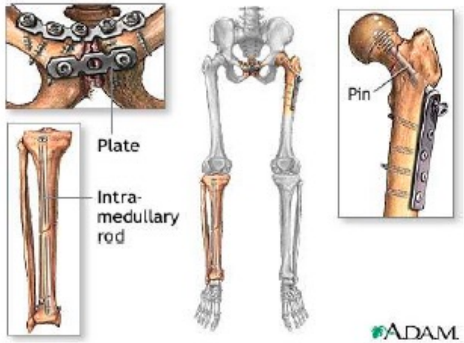
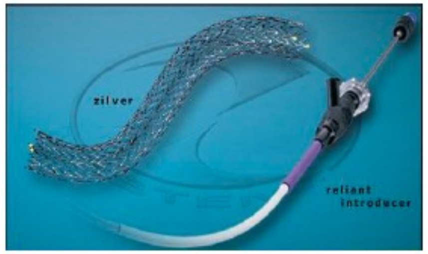
Introduction

- This class of material is known for their high stiffness, ductility, wear resistance, and thermal and electrical conductivity.
- Metals and their alloys are commonly used in implants and medical device manufacture.
- Due to their mechanical reliability, metallic biomaterials are difficult to replace with ceramic and polymer substitutes.
- One of the advantages of using metals as biomaterials is their availability and relative ease of processing from raw ore to finished products.
- The material properties of metals have been studied in the context of biocompatibility, surface interaction and structural integrity.
- Moreover, customized properties, including flexibility, high strength and abrasion resistance, can be developed by alloying constituent elements of different metals.
- Metallic biomaterials are classified as inert because they illicit minimal tissue response. Given their higher fatigue strength and chemical resistance to corrosion, they are used in load-bearing applications.









Advantages and disadvantages of metallic Biomaterials:

- ***Advantages***
- High strength.
- High hardness.
- Fatigue and impact resistance.
- Wear resistance.
- Easy fabrication.
- Easy to sterilize.
- Shape memory.

Disadvantages

- High modulus.
- High corrosion.
- Metal ion sensitivity and toxicity.

METALLICI MPLANT MATERIALS

- Metals have been used in various forms as implants.
- The first metal developed specifically for human use was “Sherman Vanadium Steel,” which was used to manufacture bone fracture plates and screws.
- Most metals used for manufacturing implants (e.g., Fe, Cr, Co, Ni, Ti, Ta, Mo, and W) can be tolerated by the body in minute amounts.
- Sometimes those metallic elements, in naturally occurring forms, are essential in cell functions (Fe), synthesis of a vitamin B12 (Co), but cannot be tolerated in large amounts in the body.
- The biocompatibility of implant metals is of considerable concern because they can corrode in the hostile body environment. The consequences of corrosion include loss of material, which will weaken the implant, and probably more important, that the corrosion products escape into tissue, resulting in undesirable effects.

STAINLESS STEELS

- Stainless steels are widely used in the biomedical field due to their excellent mechanical properties, corrosion resistance, biocompatibility, and cost-effectiveness.
- Below is an overview of stainless steels in the context of biomaterials:

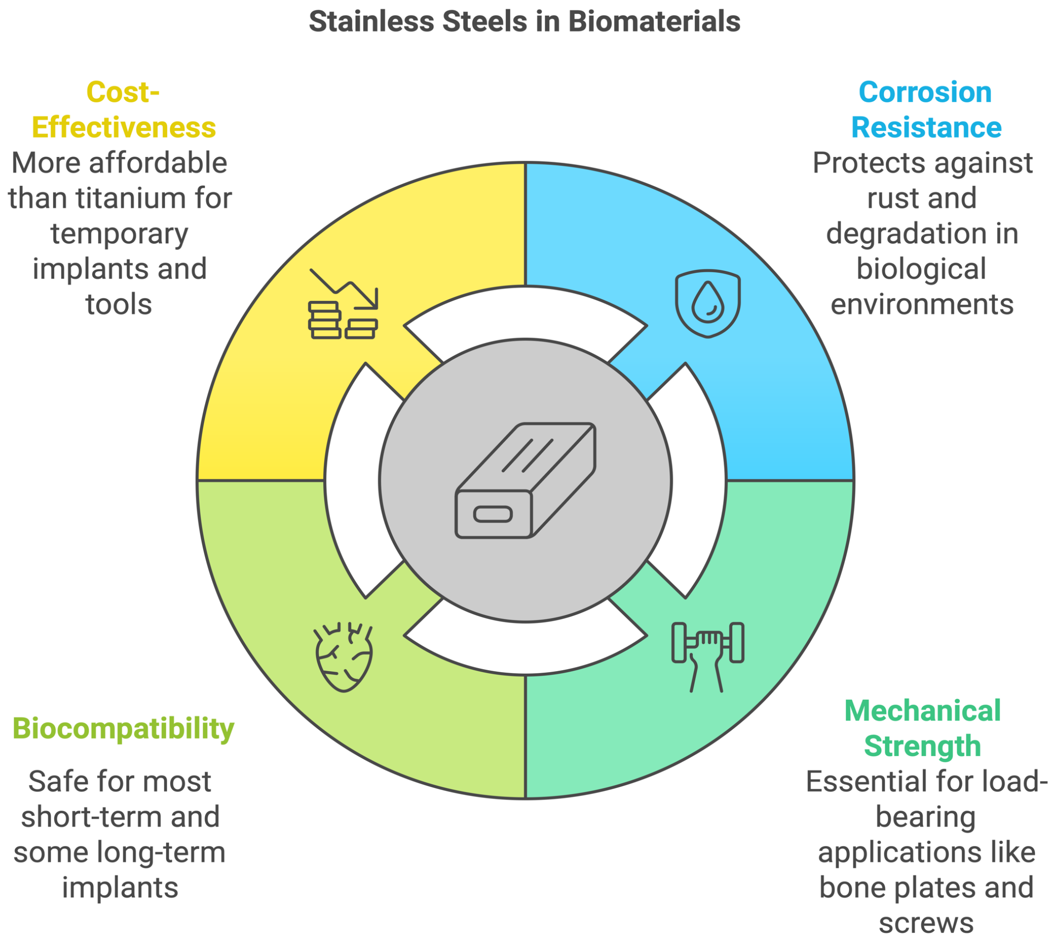
Applications of Stainless Steels in Biomedical Fields

•**Orthopedic Applications**:
  - Bone plates, screws, pins, and nails.
  - Temporary fracture fixation devices.

•**Cardiovascular Devices**:
  - Stents, heart valves, and pacemaker housings.

•**Surgical Instruments**:
  - Scalpels, forceps, retractors, and scissors.

•**Dental Applications**:
  - Orthodontic brackets and wires.



STAINLESS STEELS

- **Types of Stainless Steels Used in Biomedical Applications**

The most common stainless steel grades used in biomedical applications include:

1. Austenitic Stainless Steel (e.g., 316L):

- **Composition**: Contains chromium (16–18%), nickel (10–14%), and molybdenum (2–3%).
- **Features**:
  - Excellent corrosion resistance in physiological environments due to molybdenum.
  - Low carbon content ("L" in 316L) minimizes carbide precipitation, which improves corrosion resistance.
  - Used in orthopedic implants, cardiovascular stents, and surgical tools.

2. Martensitic Stainless Steel (e.g., 420, 440C):

- **Composition**: High carbon and chromium content.
- **Features**:
  - Excellent hardness and wear resistance.
  - Lower corrosion resistance than austenitic grades.
  - Commonly used for surgical instruments like scalpels and forceps.

3. Precipitation-Hardening Stainless Steel (e.g., 17-4PH):

- **Composition**: Chromium (15-17%), nickel (3-5%), and copper or niobium.
- **Features**:
  - High strength and moderate corrosion resistance.
  - Good for applications requiring high mechanical performance.

Limitations of Stainless Steels in Biomedical Applications

- **Susceptibility to Pitting and Crevice Corrosion**:
  In chloride-rich environments (like body fluids), stainless steel can suffer localized corrosion, particularly if the passive layer is damaged.
- **Nickel Sensitivity**:
  Some stainless steels (e.g., 316L) contain nickel, which can cause allergic reactions in sensitive individuals.
- **Limited Biocompatibility**:
  Although stainless steel is biocompatible, it does not integrate with bone or tissue as well as titanium does.
- **Fatigue and Wear**:
  In long-term implants, stainless steel may fatigue or wear out faster compared to cobalt-chromium or titanium alloys.

Co-Cr alloys

Cobalt-Chromium (Co-Cr) alloys have been extensively used in biomedical applications due to

- **High Strength and Toughness**:
  Co-Cr alloys possess high tensile strength and excellent fatigue resistance, making them ideal for load-bearing implants.
- **Corrosion Resistance**:
  Chromium (Cr) in Co-Cr alloys forms a protective oxide layer (Cr_2O_3) that offers excellent corrosion resistance, especially in body fluids.
- **Wear Resistance**:
  Co-Cr alloys exhibit superior wear resistance, which is crucial for applications like joint replacements that involve friction.
- **Biocompatibility**:
  Co-Cr alloys are biocompatible and do not cause significant adverse reactions in the body, although concerns about cobalt and chromium ion release exist in some cases.

Co-Cr alloys

1- The CoCrMo alloy [Cr (27-30%), Mo (5-7%), Ni (2.5%)] has been used for many decades in dentistry, and in making artificial joints;

2- The CoNiCrMo alloy [Cr (19-21%), Ni (33-37%), and Mo (9-11%)] has been used for making the stems of prostheses for heavily loaded joints, such as knee and hip.

Advantages of Co-Cr Alloys in Biomedical Applications

1. **Excellent Mechanical Properties**:
Co-Cr alloys can withstand high stress and strain, making them suitable for load-bearing implants.
2. **Superior Wear Resistance**:
The alloys resist wear under repeated motion, making them ideal for joint replacements.
3. **Corrosion Resistance**:
The chromium oxide layer protects against corrosion in the physiological environment.
4. **Biocompatibility**:
Co-Cr alloys are generally well-tolerated by the body, with minimal immune or inflammatory response.

Limitations of Co-Cr Alloys

1. **Metal Ion Release**:
Wear or corrosion can release cobalt and chromium ions into the body, which may lead to localized toxicity or allergic reactions in some patients.
2. **High Elastic Modulus**:
Co-Cr alloys have a much higher elastic modulus compared to bone, which can lead to stress shielding (bone loss due to reduced mechanical loading).
3. **Difficult Machinability**:
Co-Cr alloys are harder to machine or process compared to other biomaterials like titanium.

Ti and its alloy

- Titanium and its alloys are widely regarded as one of the most effective biomaterials for medical applications due to their exceptional mechanical properties

a. Corrosion Resistance

- Titanium alloys form a stable, protective oxide layer (TiO_2) on their surface, which makes them highly resistant to corrosion in physiological environments, including saline and body fluids.

b. Biocompatibility

- Titanium is bioinert, meaning it does not cause adverse reactions in the body. It also promotes osseointegration, where bone cells grow and attach to its surface, making it ideal for long-term implants.

c. High Strength-to-Weight Ratio

- Titanium alloys are lightweight (density ~4.5 g/cm^3) yet strong, making them suitable for load-bearing applications with minimal strain on the body.

d. Low Elastic Modulus

- Titanium alloys have an elastic modulus (~110 GPa) closer to that of bone (~30 GPa) compared to other metallic biomaterials like stainless steel or cobalt-chromium alloys. This reduces stress shielding, helping to maintain healthy bone density.

e. Excellent Fatigue and Wear Resistance

- Titanium alloys have high fatigue strength, crucial for implants subjected to repeated loading, such as hip and knee replacements.

Ti and its alloy

- **a. Commercially Pure Titanium (CP-Ti, ASTM F67)**
- **Composition**: Nearly pure titanium (>99%).
- **Features**:
  - Excellent corrosion resistance and biocompatibility and Moderate mechanical strength.
- **Applications**:
  Dental implants and some load-bearing implants.
- **b. Ti-6Al-4V (Grade 5, ASTM F136)**
- **Composition**: ~6% aluminum, ~4% vanadium, balance titanium.
- **Features**:
  - High mechanical strength and fatigue resistance.
- **Applications**:
  Hip joints, bone plates, screws, spinal fixation devices, and dental implants.

c. Beta Titanium Alloys (e.g., Ti-15Mo, Ti-13Nb-13Zr)

- **Composition**: Alloyed with molybdenum, niobium, zirconium, and/or tantalum.
- **Features**:
  - A lower elastic modulus than alpha or alpha-beta titanium alloys reduces stress shielding.
  - Excellent corrosion resistance and biocompatibility.
- **Applications**:
  Bone implants, spinal devices, and cardiovascular stents.

Advantages of Titanium Alloys in Biomedical Applications

1. **Lightweight**: Minimizes stress on surrounding tissues and improves patient comfort.
2. **High Mechanical Performance**: Suitable for load-bearing applications and implants with complex geometries.
3. **Osseointegration**: Promotes direct bonding with bone tissue for long-term stability.
4. **Non-Magnetic**: Safe for use in MRI and other imaging environments.

Limitations of Titanium Alloys

1. **Wear Debris**: Titanium alloys can produce wear particles in joint replacements, which may lead to inflammation or implant loosening over time.
2. **Titanium fretting wear** compared to cobalt-chromium alloys.
3. **Cost**: Titanium and its alloys are more expensive to manufacture and process than stainless steel.

mechanical properties of metallic biomaterials

- **The following table compares mechanical properties of metallic biomaterials with bone.**
- Table (1): Comparison of mechanical properties of metallic biomaterial with bone.

Material	Young's Modulus, E (GPa)	Yield Strength, σy (MPa)	Tensile Strength, σUTS (MPa)	Fatigue Limit, σend (MPa)
Stainless steel	190	221–1213	586–1351	241–820
Co-Cr alloys	210–253	448–1606	655–1896	207–950
Titanium (Ti)	110	485	760	300
Ti-6Al-4V	116	896–1034	965–1103	620
Cortical bone	15–30	30–70	70–150	

DENTAL METALS

Dental amalgam is an alloy made of liquid mercury and other solid materials particulate alloys made of silver, tin, copper, etc.

Mercury (Hg): ~50% by weight, serves as the binder.

Silver (Ag): ~22–32%, provides strength and corrosion resistance.

Tin (Sn): ~14%, enhances plasticity but can reduce strength.

Copper (Cu): ~8%, increases strength and reduces corrosion.

Depending on the formulation, amalgam can be classified as **low-copper** or **high-copper** amalgam. High-copper amalgams are preferred in modern practice due to their improved mechanical properties and reduced corrosion.

The rationale for using **amalgam as a tooth filling** material is that since mercury **is a liquid at room temperature**, **it can react with other metals such as silver and tin and form a plastic mass** **that can be packed into the cavity, and which hardens (sets) with time**

Dental amalgam

Advantages

- **Durability**:
  Amalgam fillings are highly resistant to wear and can last 10–15 years or more, making them ideal for large, load-bearing restorations (e.g., molars).
- **Strength**:
  It can withstand significant chewing forces without fracturing.
- **Ease of Use**:
  Amalgam is relatively easy to manipulate during placement and adapts well to cavity walls.
- **Cost-Effectiveness**:
  Dental amalgam is less expensive compared to other restorative materials like composite resin or ceramics.
- **Moisture Tolerance**:
  Unlike composite fillings, amalgam is less sensitive to moisture during placement.

Disadvantages

- **Aesthetics**:
  Amalgam has a metallic appearance and does not match the color of natural teeth, making it less desirable for visible restorations.
- **Mercury Content**:
  Concerns exist regarding mercury exposure during placement and removal, although studies indicate that the levels released are generally within safe limits for patients.
- **Cavity Preparation**:
  Amalgam fillings require removing more healthy tooth structure to create retention form, which is not ideal for minimally invasive dentistry.
- **Thermal Conductivity**:
  Amalgam conducts heat and cold, which can lead to temporary thermal sensitivity in some patients.
- **Environmental Concerns**:
  Improper disposal of mercury-containing amalgam can impact the environment. Many countries have strict regulations for amalgam waste management.

Noble Metals

- Noble metals show a marked reluctance to combine with other elements to form compounds. As such, they have excellent resistance to corrosion or oxidation and are good candidates for biomaterials. Noble metals such as gold, silver and platinum are used when functionality is needed other than the basic mechanical performance. Typically, they are used in devices requiring specific electrical or mechanical properties.

Gold

- Gold is an inert metal that has high resistance to bacterial colonization.
- Gold and its compounds have been historically used in oriental cultures to treat ailments.
- It has been one of the first materials to be used as an implantable material (dental tooth implant). Due to its high malleability it is used in **restorative dentistry** for crowns and permanent bridges.
- Gold possesses excellent electrical conductivity and biocompatibility and is used in wires for **pacemakers** and other medical devices.

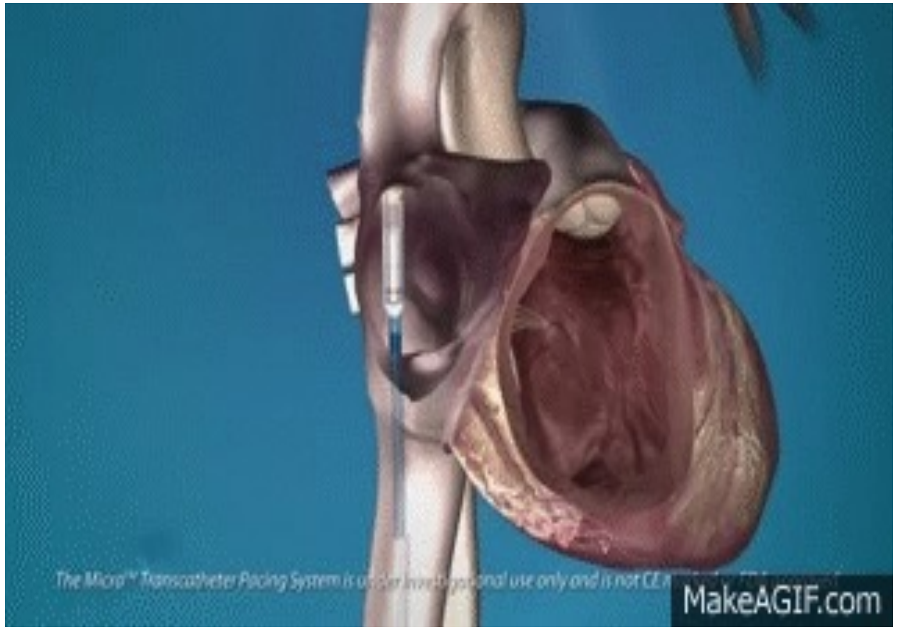
Platinum

- Platinum possesses excellent corrosion resistance, biocompatibility, and stable electrical properties.
- It is used for manufacture of electrodes in devices such as cardiac pacemakers and electrodes in cochlear (cavity within the inner ear) replacement for the hearing impaired.
- A typical pacemaker uses platinum-iridium electrodes that send electrical pulses to stabilize the rhythm of the heartbeat.

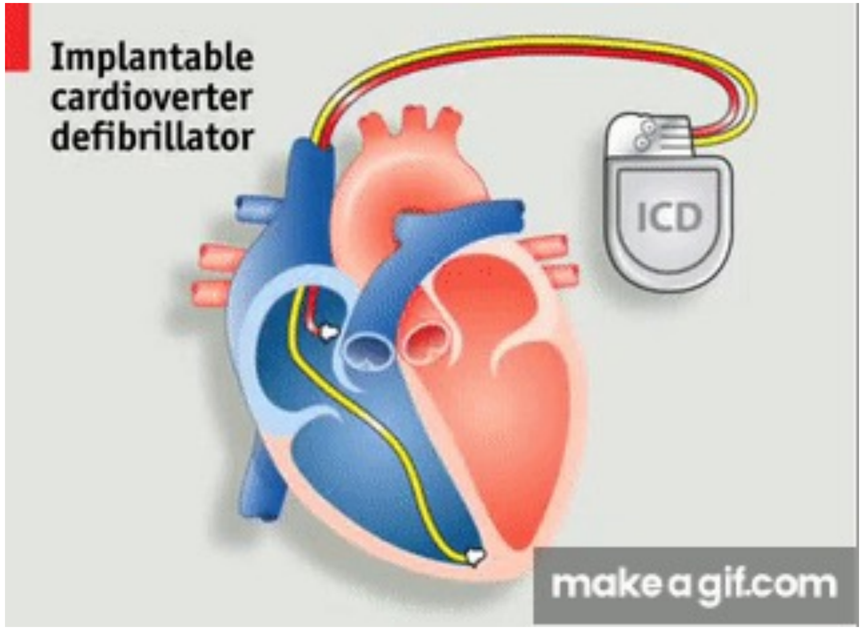
Silver

- Silver is used in surgical implants and as a sanitizing agent.
- They are used as earring studs to prevent infection of newly pierced ears.
- Silver compound is used in burn therapy to improve the healing and prevent infection of burns.
- Silver is also used in urinary bladder catheters and stethoscope diaphragms.

Case study



Leadless Cardiac Pacemaker



Pacemaker

Design and Structure:
•**Leadless Pacemaker**: Small device implanted directly in the heart; no wires or leads.
•**Traditional Pacemaker**: Larger device implanted under the skin with wires connected to the heart.

Implantation Method:
•**Leadless Pacemaker**: Inserted via catheter; less invasive procedure.
•**Traditional Pacemaker**: Requires more invasive surgery to position the device and leads.

Performance:
Leadless Pacemaker: Sends electrical pulses directly to the heart; effective for specific rhythm disorders.
Traditional Pacemaker: Offers more flexibility in pacing adjustments; suitable for various heart conditions.

Case study 2


SAMPLE
Total Hip
Replacement
Surgery
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Failure of metals for biomedical devices

1- Corrosion

Metal implant s are prone to corrosion during their services due to the corrosive medium of the implantation site.

2- Fatigue and fracture

During its service, most metallic implants are subjected to cyclic loading inside the human body, which leads to the possibility of fatigue fracture.

Factors that determine the fatigue behaviour of implant materials include the microstructure of the implant materials.

3- Wear

- With the corrosion process, wear is among the surface degradation limiting the use of metallic implants such as Ti alloy.
- Removal of dense oxide film, which naturally formed on the surface of this metallic implant, in turn caused the wear process.
- In fact, the major factor that causes premature failure of hip prostheses is the wear process, with multiple variables interacting and thus increasing the resultant wear rates.

Corrosion

- Corrosion is the deterioration of a metal due to chemical reactions between it and the surrounding environment.

The types of corrosion in metallic implants are,

Pitting: Pitting corrosion occurs when localized areas of the metal surface are attacked, forming small pits or holes. This type of corrosion is often initiated by the breakdown of the protective oxide layer (e.g., on titanium or cobalt-chromium alloys) due to chloride ions in body fluids.

Crevice: Occurs in confined spaces or crevices, such as the gaps between screws, plates, or implant interfaces, where oxygen diffusion is restricted. This creates a difference in oxygen concentration, leading to localized corrosion.

Corrosion Fatigue: Corrosion fatigue results from combined cyclic mechanical loading and a corrosive environment. Repeated stress weakens the protective oxide layer, accelerating corrosion.

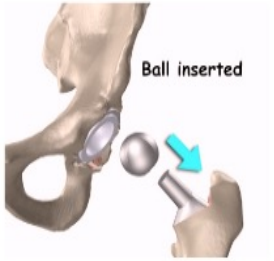
Stress-corrosion Cracking (SCC) : SCC occurs when tensile stresses (from mechanical loading or residual stresses) combine with a corrosive environment, forming and propagating cracks.

Fretting: Fretting corrosion occurs at the contact surfaces of two components (e.g., in modular implants or screws) due to micromotions that damage the protective oxide layer. This leads to wear and corrosion at the interface.

Galvanic Corrosion: Galvanic corrosion occurs when two dissimilar metals come into electrical contact in a corrosive environment (e.g., stainless steel and cobalt-chromium alloys in the same implant). The less noble metal becomes the anode and corrodes preferentially.

Corrosion

Table 7. **Types of Corrosion in the Conventional Materials Used for Biomaterial Implants**

Type of Corrosion	Material	Implant Location	Shape of the Implant
Pitting	304 SS, Cobalt based alloy	Orthopedic/ Dental alloy	
Crevice	316 L stainless steel	Bone plates and screws	
Stress Corrosion cracking	C0CrMo, 316 LSS	Only in *in vitro*	
Corrosion fatigue	316 SS, CoCrNiFe	Bone cement	
Fretting	Ti6Al4V, CoCrSS	Ball Joints	
Galvanic	304SS/316SS, CoCr+Ti6Al4V, 316SS/Ti6Al4V Or CoCrMo	Oral Implants Skrews and nuts	
Selective Leaching	Mercury from gold	Oral implants	

Thank you for your Kind Attention